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Design and experimental validation of a pendulum energy harvester with string-driven single clutch mechanical motion rectifier

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A B S T R A C T

This work presents a pendulum kinetic energy harvester with a unique mechanical motion rectifier design which uses a string-driven rectifier (SDR) with just a single clutch to convert bidirectional input oscillation of a pendulum to the unidirectional rotation of a DC motor to produce electricity. Unlike typical mechanical rectifiers which use two clutches, this rectification system has no gearing, minimising the complexity and weight of the rectifier for the energy harvester. Through experimentation, the energy harvester was found to have a normalised average power output of 4.39 W/g^2 and a normalised average power density of 5.85 W/g^2/kg when excitation was applied at the 1.5 Hz resonant frequency with a 0.75 kg pendulum mass. This corresponds to a normalised average voltage production of 55.47 V/g. Time-domain analysis of the transducer showed the successful operation of the SDR. By selectively harvesting kinetic energy during different stages of the pendulum motion, the kinetic energy of the pendulum mass was extracted while the stored potential was preserved and converted to kinetic. This allowed a high pendulum velocity to be maintained, while the rectified input motion generated a single polarity voltage from the DC motor. The construction of this system has advantages over existing designs by reducing the complexity of rectification mechanisms, providing an alternative approach to mechanical motion rectification for pendulum vibration energy harvesters.

1. Introduction

The applications and demand for low-frequency vibration energy harvesters continue to become ever greater with the increasing prevalence of battery powered portable electronics and the persistent developments in autonomous vehicles and remote sensors requiring localised power sources. Small-scale vibration energy harvesting transducers can take many forms, including piezoelectric [1–3], triboelectric [4–6], and electromagnetic designs [7–9], although there remains a need for the improved viability of devices capable of operating in low frequency environments such as the 0.5–3.5 Hz range found on the ocean surface [10]. At the multi-watt level, electromagnetic transducers have been utilised to harvest either linear [11–13] or rotational [14–16] motion, by direct-drive or through inertial excitation. Early examples of simple inertial vibration energy harvesters come from Rome et al. [17], who developed a linear device capable of harvesting energy from a backpack during human walking, and from Toh et al. [18,19] whereby a rotary pendulum was used to harness vibration from ocean waves. In both cases, input motion was transmitted directly through a rack and pinion to generate rotational motion of a DC motor generator to produce electricity. This arrangement meant that the generator would stop and reverse direction in time with the input excitations. More recent energy harvesters of this type have incorporated mechanical rectifier systems designed to maintain unidirectional rotation of the output DC motor in order to improve energy conversion efficiency [20]. Marszal et al. [21] implemented a basic version of this through the use of a single one-way clutch between a pendulum and a motor, creating a half-wave mechanical rectifier with the pendulum only driving the output in one direction. The drawback of this design is the limited power generation due to the long downtime between engagement and disengagement of the clutch and motor output, which causes a loss of motor speed and hence limits the energy conversion efficiency. In order to improve upon this, many transducers have used two one-way clutches in various arrangements to rectify both directions of an input excitation into a single unidirectional rotational output. The use of this type of rectification is common in direct-drive linear transducers, such as those used in railway tracks and vehicle suspensions [22,23], and these concepts can be applied to inertial devices as well. One such device

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was presented by Liang et al. [24], which used clutches mounted within driven bevel gears to fully rectify the oscillatory motion of a pendulum. This system is effective at rectifying the rotation of the pendulum mass; however, an alternative design by the present authors [25,26] demonstrated a significantly higher power density, incorporating a mechanical rotation rectifier system comprised of spur gears. These two devices both use the minimum number of gears possible to achieve the desired rectification, and yet these gearing systems still add significant mass and volume to the energy harvesters.

This work presents an alternative approach to mechanical rectification of pendulum vibration energy harvesters, introducing a system capable of converting bidirectional input motion to the unidirectional rotation of a DC motor using a rectifier with just a single clutch and no gearing. By taking advantage of the singular direction of rotation of a pulley when an attached string is pulled, a string-driven rectifier (SDR) has been designed to capture the kinetic energy of a pendulum during the time for which its angular displacement is increasing. Since frictional losses are minimal, by not harvesting during the return swing of the pendulum, the remaining potential energy from the mass can be converted to usable kinetic energy, allowing the pendulum to maintain a high velocity. This novel design has the potential to reduce the complexity and weight of vibration energy harvester rectifiers and can be applicable to any such harvester where displacement may be used to create an extension of the string.

2. Designed pendulum energy harvester with SDR

Fig. 1 shows the overall design of the pendulum energy harvester with SDR. The device consists of a pendulum frame, mass, pendulum arm, SDR rectifier assembly, and a geared DC motor. The pendulum arm is fixed to a shaft which is held by two bearings to form the central pivot. At the end of the arm is the pendulum mass, an input vibration causes the mass to gain inertia which leads to rotation of the pendulum arm about the pivot. The high tensile strength braided drive string is also fixed at one end to the pendulum arm in the same location as the mass, with the other end located within the rectifier

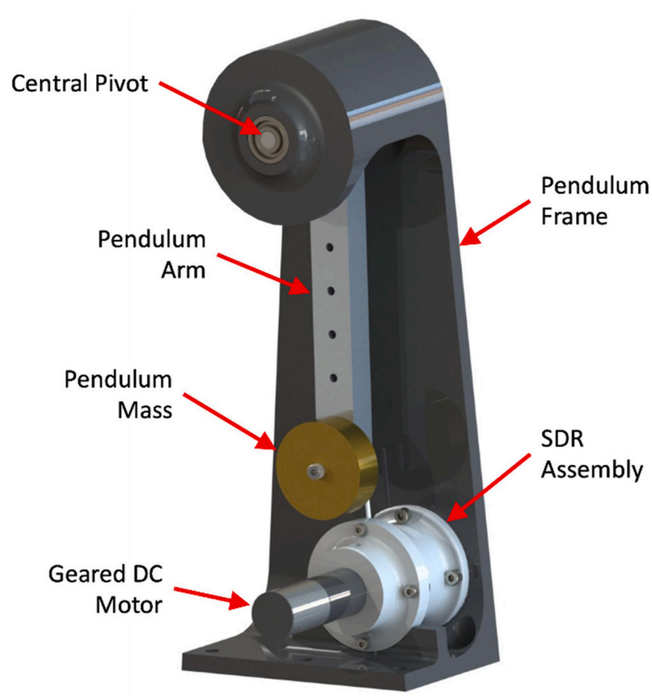


Fig. 1. Overall design of pendulum vibration energy harvester with SDR.

assembly. As shown in Fig. 2, the string is always extended when the pendulum is displaced from its resting position, regardless of the direction of travel. The working mechanism of the SDR is shown in Fig. 3. The return spring is connected at its outer end to the inside of the drive pulley, with the inner end of the spring fixed to the clutch housing. Within the clutch housing, the one-way clutch is mounted via an interference fit, with the output shaft fixed on the inner race of the clutch in the same way. The output shaft is hollowed at its end, such that the geared DC motor shaft is mounted within it and held by a small grub screw. The body of the geared motor is then secured to the rectifier housing via three fixing bolts. The DC motor used is a Maxon A-Max 22 mm brushed DC motor, mounted to a Maxon 19:1 22 mm planetary gearhead (Maxon Motor UK Ltd., Berkshire, UK). This combination was chosen for its high efficiency, as well as the low stall-torque of the motor and high torque capabilities of the gearhead.

As shown in Fig. 4, the pulley rotates in the clockwise direction when the magnitude of the displacement of the pendulum is increasing (Fig. 4(a & c)). During this clockwise rotation, the clutch is engaged which rotates the output shaft to drive the geared DC motor while at the same time compressing the return spring. In this way, the DC motor is only driven during the periods for which the kinetic energy of the mass is being converted into potential energy. When the displacement of the pendulum is decreasing (Fig. 4(b & d)) and the mass travels towards the central position, the string is no longer being extended so the clutch freewheels and the tension of the return spring is releasing which rotates the drive pulley in the anticlockwise direction, maintaining tension on the string. This means that the DC motor is no longer driven, which reduces the damping on the system and allows the mass to maintain its stored potential and convert it to kinetic energy during this stage of motion where the pendulum velocity is increasing. Due to the limited friction in the system during disengagement, most of this energy is conserved, and hence there is minimal loss from not having full rectification of the input motion.

This conservation of potential energy allows the pendulum arm to maintain a high speed throughout operation. Therefore, this simplified, compact rectifier is able to successfully convert kinetic energy from a pendulum system into electrical energy, using minimal components with no gearing, including just a single one-way clutch. Another benefit of this rectifier design, as seen in Figs. 2–4, is that it simply requires an extension of a string. Unlike many existing mechanical rectifiers which can harvest from either rotational or linear motion, but not both, this system is capable of converting almost any mechanical displacement into unidirectional rotation of the DC motor generator.

3. Mathematical description of the pendulum energy harvester with SDR

To simplify the mathematical analysis, the schematic of the SDR pendulum is shown in Fig. 5. The pendulum system is comprised of a pendulum mass, m_M, fixed to a pendulum arm with a length of l_M which rotates about its centre of rotation, O, when a harmonic horizontal excitation of $A\cos(\omega_f t)$ is applied. The end of the pendulum arm is connected by a string to a pulley centred at point P with a radius r_P. This pulley contains a return spring and clutch such that it drives the output to harvest the kinetic energy of the pendulum mass only in the clockwise direction while the magnitude of the angular displacement of the pendulum arm is increasing (i.e., when moving away from the vertical equilibrium position). When the magnitude of displacement of the arm is reducing (i.e., when it moves towards vertical), the clutch freewheels and the string is able to retract under tension from the return spring, allowing the gathered potential energy of the mass to be converted to kinetic to maintain a high speed of the pendulum arm. The freewheeling of the

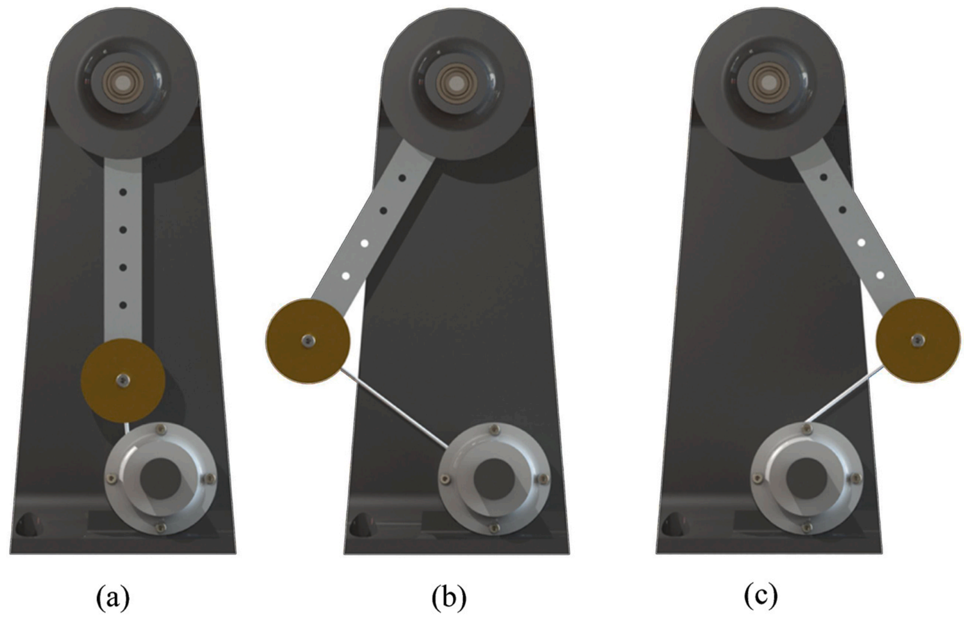


Fig. 2. Pendulum operation at different locations, demonstrating extension of the string (a) where θ = 0, with no extension of the string, (b) clockwise rotation of the pendulum, with extension of the string, and (c) anti-clockwise rotation of the pendulum, also with extension of the string.

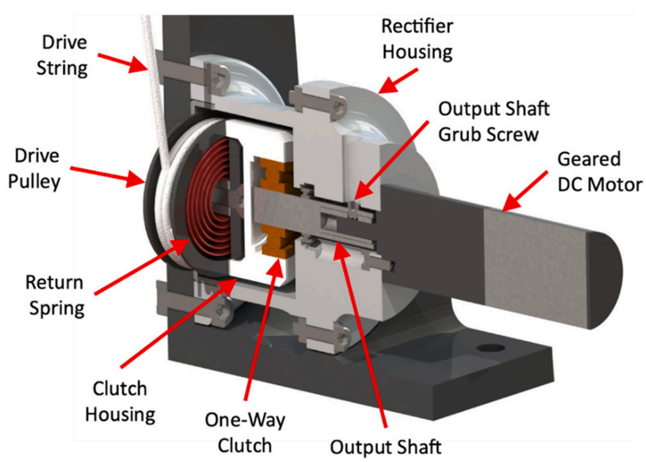


Fig. 3. Working mechanism of the string-driven rectifier.

clutch, and therefore decoupling of the pendulum mass and DC motor rotations, can be summarised as occurring under the following conditions:

1) $\dot{\theta} n_P n_G < \dot{\theta}_{GB}$ (The DC motor is rotating faster than the output shaft, so is no longer driven)
2) $\theta > 0$ & $\dot{\theta} < 0$ (The pendulum arm is rotating clockwise, towards the y-axis position)
3) $\theta < 0$ & $\dot{\theta} > 0$ (The pendulum arm is rotating anticlockwise, towards the y-axis position)

where $\dot{\theta}$ is the rotational velocity of the pendulum arm, $\dot{\theta}_{GB}$ is the rotational velocity of the DC motor, and n_P and n_G are the equivalent gear ratios of the arm/pulley and gearhead, respectively.

The system can therefore be described by the following differential equations during the coupled and decoupled stages of operation:

Coupled

$$(J_M + J_G n_P^2 n_G^2 + J_{GB} n_P^2)\ddot{\theta} + (c_E + c_{MP} + c_{MG})\dot{\theta} + k l_M \theta +$$

$$m_M l_M \, g \, sin\theta = m_M l_M \, cos\theta \, A\cos(\omega_f t) \quad (1)$$

Decoupled

$$J_M \ddot{\theta} + c_{MP}\dot{\theta} + m_M l_M g sin\theta + k l_M \theta = m_M l_M \, cos\theta \, A\cos(\omega_f t) \quad (2)$$

$$(J_G n_P^2 n_G^2 + J_{GB} n_P^2)\ddot{\theta} + (c_E + c_{MG})\dot{\theta} = 0 \quad (3)$$

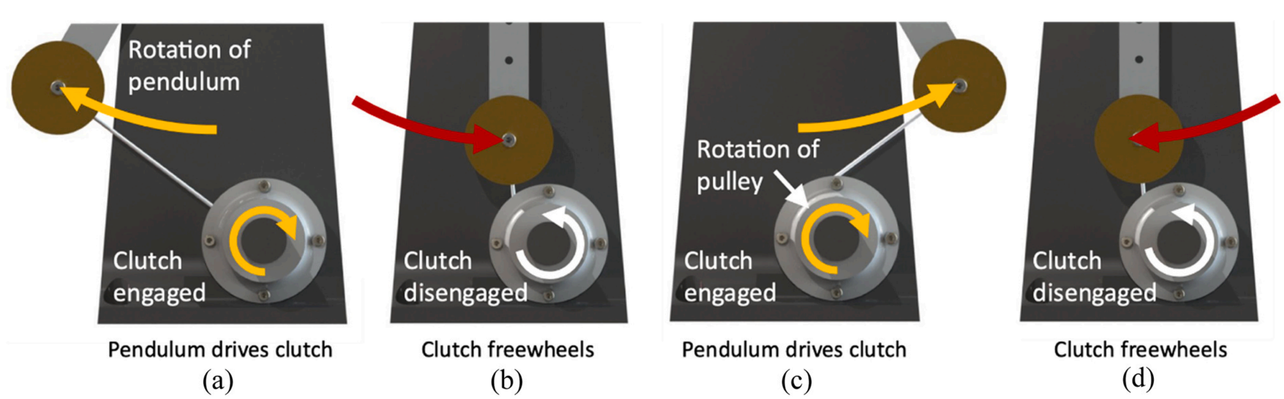


Fig. 4. Pendulum at different stages of motion, showing engagement and disengagement of the clutch.

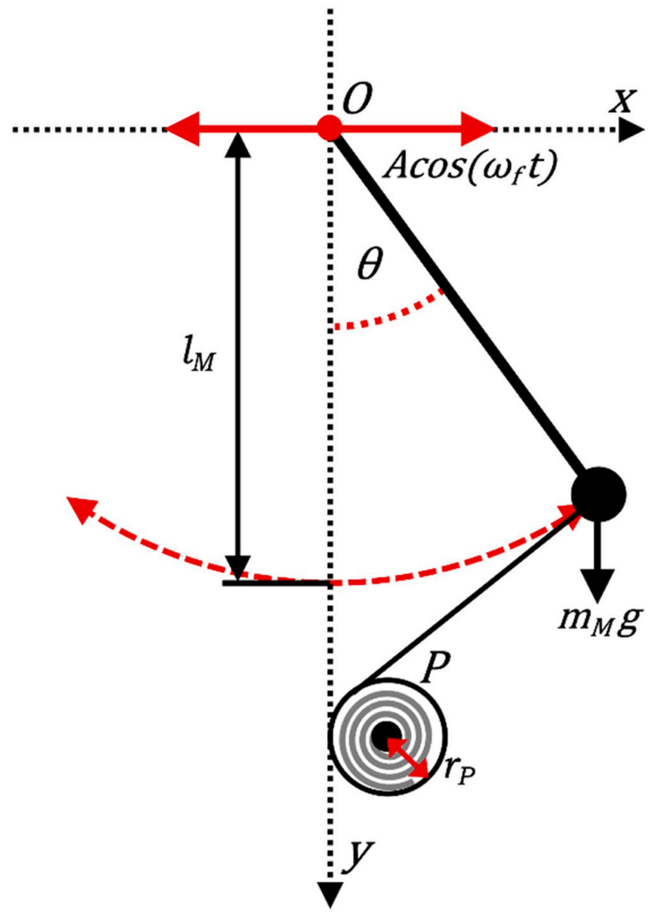


Fig. 5. Schematic of the string-driven rectifier pendulum vibration energy harvester.

where J_M, J_G, and J_{GB} are the rotational inertia of the pendulum mass, DC motor generator and gearhead, respectively, c_E is the electrical damping, and c_{MP} and c_{MG} are the mechanical damping of the pendulum side and geared motor side of the system, respectively. k is the spring constant of the torsion return spring. Due to the nature of the stiff braid used, the drive string can be treated as inextensible, thus providing direct power transfer from the pendulum arm to the pulley when the clutch is engaged.

When θ is small, the undamped resonant frequency of the pendulum, ω_n, can be described as:

$$\omega_n = \sqrt{\frac{m_M L_M \quad g + \quad kl_M}{m_M L_M^2}} \tag{4}$$

It can be seen from Eq. (4) that the addition of the spring constant, k, increases the restoring stiffness of the system, which is $m_M L_M g + kl_M$, thus increasing the natural frequency of the device.

Despite having just a single clutch, the string mechanism allows the device to harvest kinetic energy in both clockwise and anticlockwise directions. The key difference between this system and a typical two-clutch mechanical rotation rectifier [25,26] is that it harvests only the kinetic energy of the pendulum on the upswing, while permitting the pendulum to move unimpeded as it travels back towards the y-axis by not harvesting from this motion. This allows the mass to maintain all its gathered potential energy from its amplitude and, since negligible frictional losses are assumed, the pendulum, therefore, has access to a similar amount of energy as a two-clutch rectifier while simplifying the overall construction. In addition, while this work is focussed on a pendulum device, the excitation could come from any source which could lead to an extension of the string, in which case the same mathematical principles would apply. If this SDR design were to be implemented for other such applications where scaling may be required, it is known from Eqs. (1)–(3) and from previous works [25] that the power output of a pendulum energy harvester is directly proportional to the pendulum mass. This allows for larger masses to be used where greater power is desired, but it is important to note that this would also require the use of a larger clutch and gearhead, to handle the increase in torque, and a larger motor capable of converting greater amounts of energy at the typical operating speed of the system. At greater loads, the tensile strength and stiffness of the drive string should also be considered, as to withstand the increased stress and limit strain which could affect the overall stiffness of the system.

For comparison, the pendulum without the SDR can be modelled and simulated. The equivalent system without the inclusion of the clutch and spring can be described by the following equation:

$$(J_M + J_G n_P^2 n_G^2 + J_{GB} n_P^2)\ddot{\theta} + (c_E + c_M)\dot{\theta} +$$

$$(m_M l_M)\, g \, sin\theta = (m_M l_M)\, cos\theta \, Acos(\omega_f t) \tag{5}$$

where c_M is the mechanical damping coefficient for the system, which has significant influence on the power generation of harvesters; the optimal electrical damping c_E for this system at resonance, which determines the power generation capability of the harvester, can be written as:

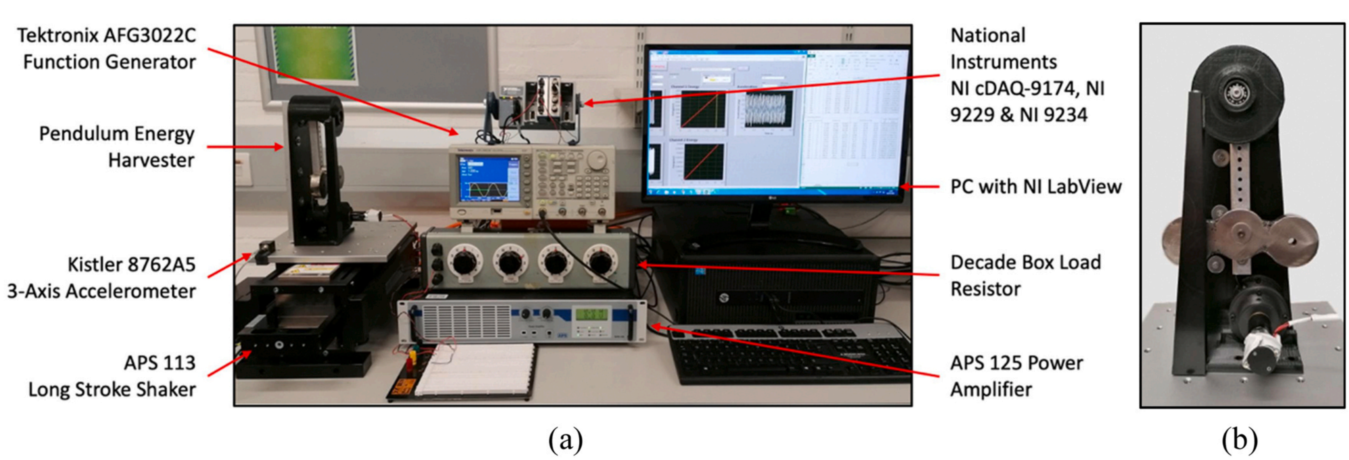


Fig. 6. (a) Experimental setup for the energy harvester, and (b) SDR pendulum energy harvester.

Table 1
Pendulum energy harvester parameters.

Energy Harvester Parameter	Value	Units
Motor nominal voltage	36	V
Motor no-load speed	9800	rpm
Motor rotor inertia	4.09	g.cm^2
Motor speed constant	274	rpm/V
Motor torque constant	34.8	nNm/A
Motor terminal resistance	60.1	Ω
Gearhead gear ratio	19.34:1	–
Ratio between the radius of the pendulum arm and the pulley of SCR	5.27:1	–
Pendulum mass	0.75	kg
Length of pendulum arm	0.158	m
Dimensions of harvester	290(H)x120(W) x220(D)	mm

$$c_E = 2J_M\,\omega_n\sqrt{\left(\frac{c_M}{2J_M\,\omega_n}\right)^2 + \frac{1}{4}\left(1-\left(1+\frac{J_G n_P^2 n_G^2 + J_{GB}\, n_P^2}{J_M}\right)\right)^2} \tag{6}$$

It is worth noting that the pendulum without the SDR requires the DC motor and gearhead to be placed at the pivot of the pendulum to allow for power transfer, whereas the SDR pendulum has an advantage in terms of design flexibility as the SDR system can be located away from the pendulum where required.

4. Experimental methods

Fig. 6 shows the experimental setup for the SDR pendulum energy harvester. The harvester was mounted to the top of an APS 113 long stroke shaker (Techni Measure Ltd., Doncaster, UK), which was powered by an APS 125 amplifier (Techni Measure Ltd., Doncaster, UK). The amplifier input signal was derived from a Tektronix AFG3022C Function Generator (Tektronix UK Ltd., Berkshire, UK), which was set up to produce a harmonic signal. To monitor the acceleration of the shaker table, a Kistler 8762A5 accelerometer (Kistler Instruments Ltd., Hampshire, UK) was mounted to it, with the signal measured through National Instruments DAQ hardware (National Instruments, Austin, Texas) and recorded using NI LabVIEW computer software. The output terminals of the energy harvester's DC motor were connected in parallel to a variable decade resistor, with the voltage across this load measured and recorded in the same way. By monitoring the output voltage across a known electrical resistive load over a period of time, the total energy production and thus the power output of the device were calculated. The overall parameters of the device are shown in Table 1.

The optimal loading condition for the energy harvester was determined through a comparison of the normalised power output of the device under different external load resistors. For this experiment, a vibration was applied to the energy harvester at its resonant frequency of 1.5 Hz with an acceleration of 0.264 g rms. To calculate the average power output, the energy extracted from the device was measured over a period of 10 s and divided by the number of seconds. This was then divided by the square of the input acceleration to give the normalised average power density. Fig. 7(a) shows the results of this load testing, demonstrating an optimal resistor value of 700 Ω which was then used for the remaining experiments. Fig. 7(b) shows the performance of the energy harvester when subjected to frequencies in the range of 1.0–2.5 Hz. This confirms the resonant frequency of 1.5 Hz, which is higher than typical pendulums of this size [25]. This is because the inclusion of the return spring increases the restoring stiffness of the device, and thus

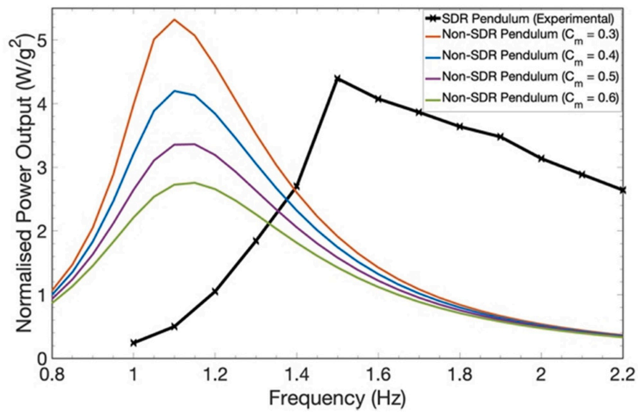


Fig. 8. Normalised average voltage output of SDR energy harvester at different frequencies, with R_L = 700 Ω, compared with simulation results of energy harvester without SDR with corresponding optimal loads.

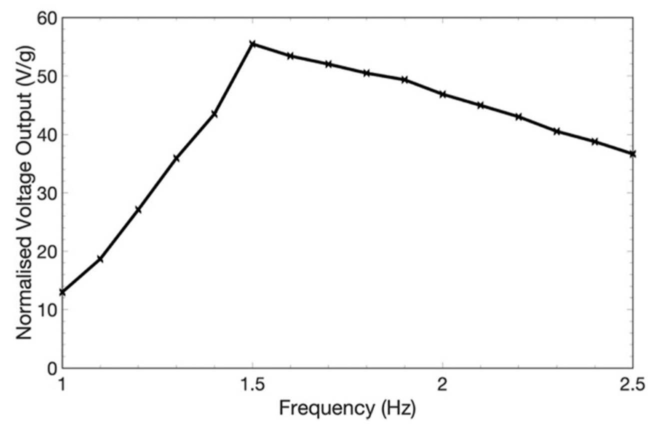
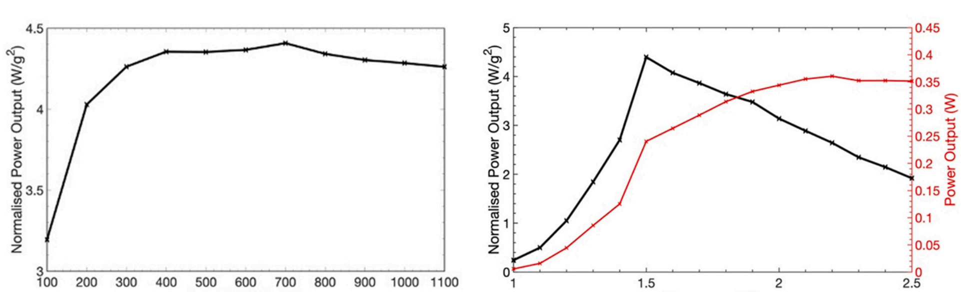


Fig. 9. Normalised average voltage output of energy harvester at different frequencies, with R_L = 700 Ω.



(a) (b)

Fig. 7. Normalised average power output of the energy harvester (a) under different external loads at ω_f = 1.5 Hz and acc. = 0.264 g rms, and (b) with varying frequency at the optimal load of R_L = 700 Ω, along with actual average power output with displacement amplitude of 150 mm peak-to-peak.

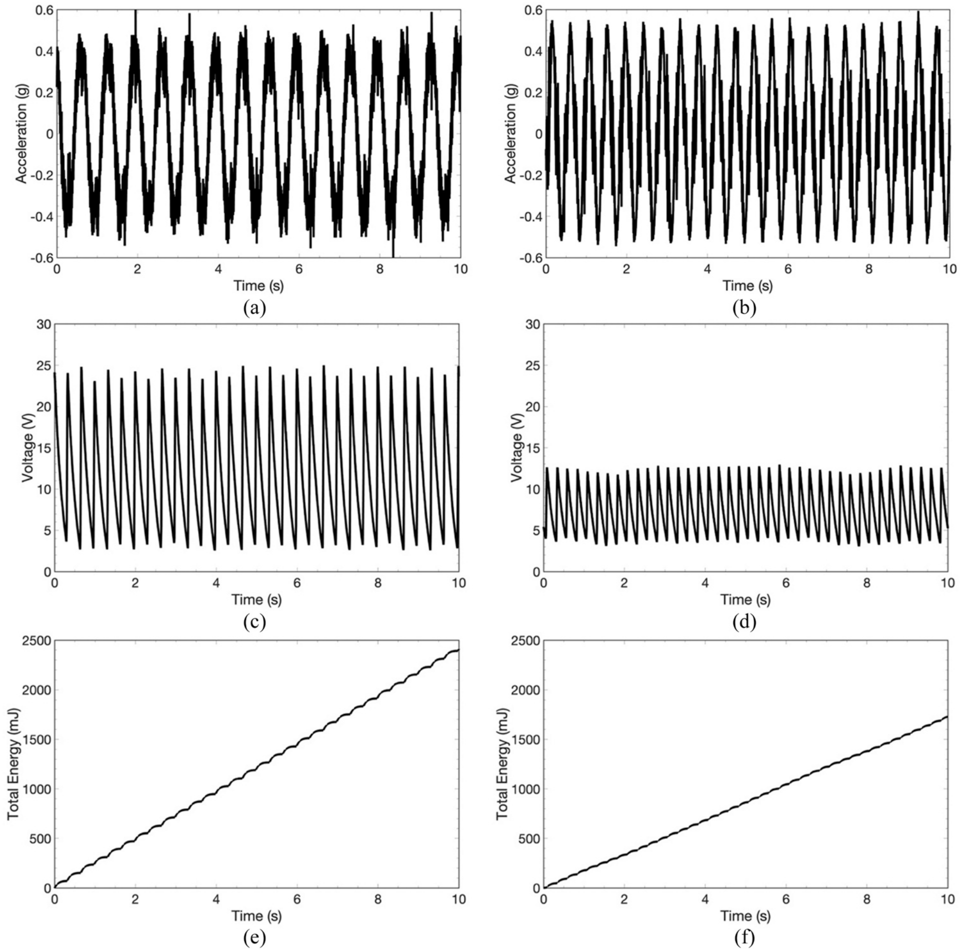


Fig. 10. Time domain inputs and outputs of the energy harvester: (a) and (b) input accelerations at ω_f = 1.5 Hz and ω_f = 2 Hz; (c) and (d) voltage outputs at ω_f = 1.5 Hz and ω_f = 2 Hz; (e) and (f) total cumulative energy at ω_f = 1.5 Hz and ω_f = 2 Hz, respectively.

increases the natural frequency above what would usually be expected of a pendulum of this length. Due to the amplitude of the excitation being maintained at the maximum displacement of the shaker, the acceleration of this vibration changed with frequency. Therefore, the power output was normalised to give an accurate representation of the capabilities of the device under different ambient conditions. From these results, the maximum normalised average power output was shown to be 4.39 W/g^2, which gives a normalised average power density of 5.85 W/g^2/kg with a 0.75 kg inertial load.

To understand the harvester with SDR, comparison with the same device without the SDR system is made and the simulation results based on Eqs. (5) and (6) have been shown in Fig. 8, demonstrating the effect of the SDR on power output. The results of the non-SDR pendulum are shown with different levels of mechanical damping coefficient within the expected range of 0.3–0.6, with each result simulated using the corresponding optimal external load as determined by Eq. (5). As expected, the SDR pendulum has a higher resonant frequency than the non-SDR system, which has a resonance of 1.15 Hz, due to the increased stiffness caused by the return spring. The corresponding normalised power output without SDR device can be higher or lower than the harvester with SDR, demonstrating the importance of the damping coefficient design for the harvester SDR. In order to generate high normalised power from the harvester without SDR, the damping coefficient has to be minimised, though this is difficult to control in practice. The corresponding normalised average voltage output of the SDR device is shown in giving a maximum value of 55.47 V/g. (Fig. 9).

To verify correct operation of the device under harmonic excitation, the time domain behaviour of the energy harvester was tested and analysed. Fig. 10 shows the voltage output and total cumulative energy produced by the DC motor at both the 1.5 Hz natural frequency and at a frequency away from the resonance of 2 Hz. Comparing the voltage from Fig. 10(c & d) to the input acceleration in Fig. 10(a & b), it can be seen that the voltage reacts as expected from the SDR. As shown in Fig. 11, when the acceleration is increasing from zero to a positive peak, the voltage is increasing, which shows the engagement of the clutch and therefore driving of the DC motor. Likewise, when the acceleration is decreasing from zero towards a negative peak, the same occurs. Any other time, while the acceleration is decreasing in magnitude, which corresponds to the pendulum moving towards zero displacement, the voltage drops showing disengagement of the clutch. Therefore, the SDR is effectively rectifying the pendulum motion as intended. From Fig. 11(b), it can be seen that the voltage begins to drop prior to disengagement of the clutch. This is due to the speed of the pendulum arm falling below that of the geared DC motor, so the inner race of the clutch is freewheeling despite the outer race still being engaged by the string. Fig. 10 (e & f) show the cumulative energy generated by this voltage waveform, demonstrating the consistent power output of the device over time.

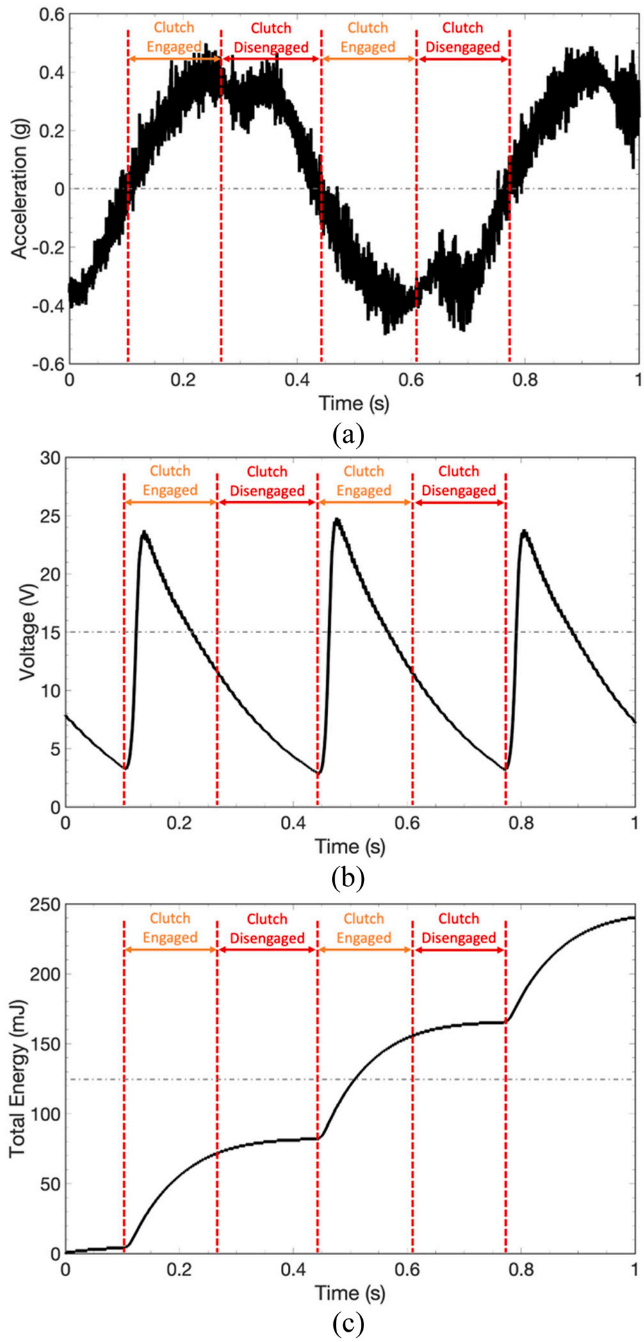


Fig. 11. Time domain response of the energy harvester showing engagement and disengagement of the clutch: (a) input acceleration at $\omega_f = 1.5$ Hz; (b) voltage output at $\omega_f = 1.5$ Hz; (c) total cumulative energy at $\omega_f = 1.5$ Hz.

5. Conclusion

This work has presented a unique approach to energy harvester mechanical rectification design to simplify pendulum vibration energy harvesters and reduce their weight. By designing, prototyping and testing this novel concept, the effectiveness of the system has been validated. The use of a string as the driving instrument for a gearless, single-clutch, pulley-driven rectifier allows for bidirectional rectification of an input in order to unidirectionally drive a DC motor; something which typically requires multiple clutches and large and heavy gearing. Empirical evaluation of this device shows a maximum normalised average power output of 4.39 W/g^2, and a corresponding normalised average power density of 5.85 W/g^2/kg, at a resonant frequency of 1.5 Hz with a 0.75 kg inertial mass. From these results, the maximum normalised voltage output of the energy harvester was measured to be 55.47 V/g. Through time-domain analysis of the voltage output from the transducer, it was shown that the device is capable of successfully rectifying the motion of the pendulum, in either direction, to the unidirectional rotation of the output DC motor during the phases for which the acceleration of the device is increasing in magnitude. This allows for kinetic energy to be extracted from the system while enabling potential energy to be conserved and converted to kinetic to preserve a high rotational speed of the pendulum arm. This design has the potential to be applicable to a range of pendulum vibration energy harvesters where it is important that complexity, size and weight are kept to a minimum.

CRediT authorship contribution statement

James Graves: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Meiling Zhu**: Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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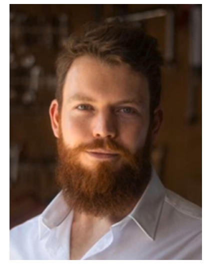
References

[1] Y. Kuang, Z.J. Chew, M. Zhu, Strongly coupled piezoelectric energy harvesters: finite element modelling and experimental validation, Energy Convers. Manag. 213 (2020) 112855.
[2] Y. Kuang, et al., Energy harvesting during human walking to power a wireless sensor node, Sens. Actuators A Phys. (2016) 254.
[3] W. Jiang, L. Wang, L. Zhao, G. Luo, P. Yang, S. Ning, D. Lu, Q. Lin, Modeling and design of V-shaped piezoelectric vibration energy harvester with stopper for low-frequency broadband and shock excitation, Sens. Actuators A Phys. 317 (2021) 112458.
[4] P. Cheng, H. Guo, Z. Wen, C. Zhang, X. Yin, X. Li, D. Liu, W. Song, X. Sun, J. Wang, Z.L. Wang, Largely enhanced triboelectric nanogenerator for efficient harvesting of water wave energy by soft contacted structure, Nano Energy 57 (2019) 432–439.
[5] J. Fu, K. Xia, Z. Xu, Double helix triboelectric nanogenerator for self-powered weight sensors, Sens. Actuators A Phys. 323 (2021) 112650.
[6] C. Hou, T. Chen, Y. Li, M. Huang, Q. Shi, H. Liu, L. Sun, C. Lee, A rotational pendulum based electromagnetic/triboelectric hybrid-generator for ultra-low-frequency vibrations aiming at human motion and blue energy applications, Nano Energy 63 (2019) 103871.
[7] Y. Kuang, R. Hide, M. Zhu, Broadband energy harvesting by nonlinear magnetic rolling pendulum with subharmonic resonance, Appl. Energy 255 (2019) 113822.
[8] B. Ambrożkiewicz, G. Litak, P. Wolszczak, Modelling of electromagnetic energy harvester with rotational pendulum using mechanical vibrations to scavenge electrical energy, Appl. Sci. 10 (2) (2020) 671.
[9] K. Fan, M. Cai, F. Wang, L. Tang, J. Liang, Y. Wu, H. Qu, Q. Tan, A string-suspended and driven rotor for efficient ultra-low frequency mechanical energy harvesting, Energy Convers. Manag. 198 (2019) 111820.
[10] Y. Yin, D. Zhao, H. Cui, M. Hong, Predicting method of natural frequency for ship's vertical vibration, Brodogradnja 65 (3) (2014) 49–58.
[11] L. Zuo, B. Scully, J. Shestani, Y. Zhou, Design and characterization of an electromagnetic energy harvester for vehicle suspensions, Smart Mater. Struct. 19 (4) (2010) 045003.
[12] Y. Kawamoto, Y. Suda, H. Inoue, T. Kondo, Electro-mechanical suspension system considering energy consumption and vehicle manoeuvre, Veh. Syst. Dyn. 46 (S1) (2008) 1053–1063.
[13] X. Zhang, Z. Zhang, H. Pan, W. Salman, Y. Yuan, Y. Liu, A portable high-efficiency electromagnetic energy harvesting system using supercapacitors for renewable energy applications in railroads, Energy Convers. Manag. 118 (2016) 287–294.
[14] W. Ding, H. Cao, B. Zhang, K. Wang, A low frequency tunable miniature inertial pendulum energy harvester, J. Appl. Phys. 124 (16) (2018) 164506.

[15] X. Chen, L. Gao, J. Chen, S. Lu, H. Zhou, T. Wang, A. Wang, Z. Zhang, S. Guo, X. Mu, Z.L. Wang, Y. Yang, A chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator for wave energy scavenging and self-powered wireless sensing system, Nano Energy 69 (2020) 104440.
[16] Y. Li et al., Design and experiment of an ultra-low frequency pendulum-based wave energy harvester, in: 2019 IEEE 14th International Conference on Nano/Micro Engineered and Molecular Systems (NEMS), 2019.
[17] L.C. Rome, L. Flynn, E.M. Goldman, T.D. Yoo, Generating electricity while walking with loads, Science 309 (5741) (2005) 1725–1728.
[18] M. Borowiec, et al., Dynamic response of a pendulum-driven energy harvester in the presence of noise, J. Phys. Conf. Ser. 476 (2013) 012038.
[19] T.T. Toh et al., Electronic resonant frequency tuning of a marine energy harvester, 2011.
[20] Z. Lei, T. Xiudong, Large-scale vibration energy harvesting, J. Intell. Mater. Syst. Struct. 24 (11) (2013) 1405–1430.
[21] M. Marszal, B. Witkowski, K. Jankowski, P. Perlikowski, T. Kapitaniak, Energy harvesting from pendulum oscillations, Int. J. Non-Linear Mech. 94 (2017) 251–256.
[22] Z. Li, L. Zuo, J. Kuang, G. Luhrs, Energy-harvesting shock absorber with a mechanical motion rectifier, Smart Mater. Struct. 22 (2) (2013) 025008.
[23] T. Lin, Y. Pan, S. Chen, L. Zuo, Modeling and field testing of an electromagnetic energy harvester for rail tracks with anchorless mounting, Appl. Energy 213 (2018) 219–226.
[24] L. Changwei, W. You, Z. Lei, Broadband pendulum energy harvester, Smart Mater. Struct. 25 (9) (2016) 095042.
[25] J. Graves, Y. Kuang, M. Zhu, Scalable pendulum energy harvester for unmanned surface vehicles, Sens. Actuators A Phys. 315 (2020) 112356.
[26] J. Graves, Y. Kuang, M. Zhu, Counterweight-pendulum energy harvester with reduced resonance frequency for unmanned surface vehicles, Sens. Actuators A Phys. 321 (2021) 112577.



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